Computational Modeling of River Flow, Sediment Transport, and Bed Evolution Using Remotely Sensed Data

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LONG-TERM GOALS

This project is focused on combining remotely sensed data for river bathymetry with computational flow models in order to make detailed predictions of flow, sediment transport and bed morphologic change in rivers. The long-term goals include developing a better characterization of the accuracy and range of applicability of remote sensing techniques for collection of river bathymetry data, assessment of errors associated with computational river model applications using remotely sensed information relative to similar applications using conventional surveying techniques, and development and distribution of public domain software for applying river models using remotely sensed data. These goals are driven by the increasing demand for river modeling applications for assessment of flow pattern, navigation, habitat, flood inundation and morphologic variation in river systems where conventional bathymetric surveys are not available and access is limited. Furthermore, even in certain situations where conventional surveys can be carried out, the use of remotely sensed data is an attractive alternative due to its relative speed and safety. The key to developing this methodology is the collection of appropriate field data in concert with modeling applications to better characterize the range of applicability and potential error; this is the central focus of the work described here.

OBJECTIVES

The specific objectives of the research work carried out under this grant are to assess errors associated with estimating river bathymetry using remote-sensing techniques and to understand how those errors propagate through the application of various computational river models. Ideally, this understanding will lead to better methods for applying river models to remotely sensed data and to specific methods for error estimation that can be incorporated into existing USGS public-domain modeling interfaces for river applications. The remote-sensing techniques considered here include multispectral and hyperspectral scanning as well as bathymetric (visible wavelength) LiDAR. In the first year of the project, work was concentrated on airborne bathymetric LiDAR data collection using the Experimental Advanced Airborne Research LiDAR (EAARL, Wright and Brock, 2002) originally developed at NASA but now operated by the USGS. Figure 1 shows a simple schematic of this methodology, which uses visible-wavelength laser light to detect bed elevations. Unlike most conventional ground-surface LiDAR, which typically use infrared laser light that is attenuated over a very short distance in water,

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the use of visible wavelength laser light allows data to be collected through the water column, provided that the depth and/or suspended material concentrations are not too large. The proposed work included bathymetric LiDAR data collection at two sites during the first year of the project and additional sites during the second year of the project. In addition, during the second year we planned to carry out multi/hyperspectral scanning at some subset of those sites. The spectral scanning techniques allow correlation of various spectral measurements or band ratios with depth; thus it is another technique for remotely sensing river characteristics. An example of this technique is shown in Figure 2. For both the spectral correlation and LiDAR techniques, this project aims to develop error estimates and to understand how those errors propagate through predictive models for river flow.

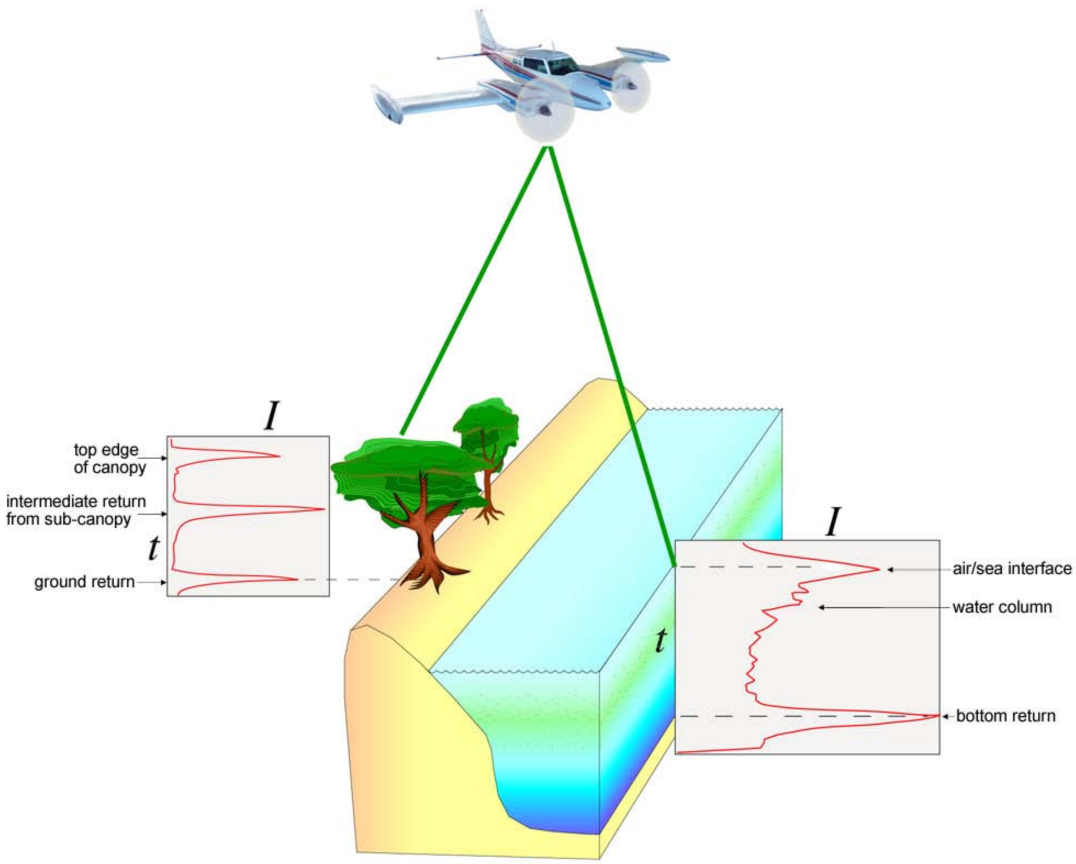


Figure 1. Schematic of temporal waveform capture by the Experimental Advanced Airborne Research LiDAR (EAARL).

APPROACH

In order to accomplish the goals of characterizing the accuracy of remotely sensed data relative to conventionally surveyed bathymetric data in rivers, bathymetric data using conventional and remote-sensing techniques on several rivers of different character and size are being collected at the same time. This field work is being coordinated by Paul Kinzel of the USGS (see also Kinzel et al, 2007). By direct comparison of the two kinds of data, it is possible to assess the errors in the remotely sensed data relative to conventional (i.e., collected using ground surveying and acoustic techniques) bathymetric

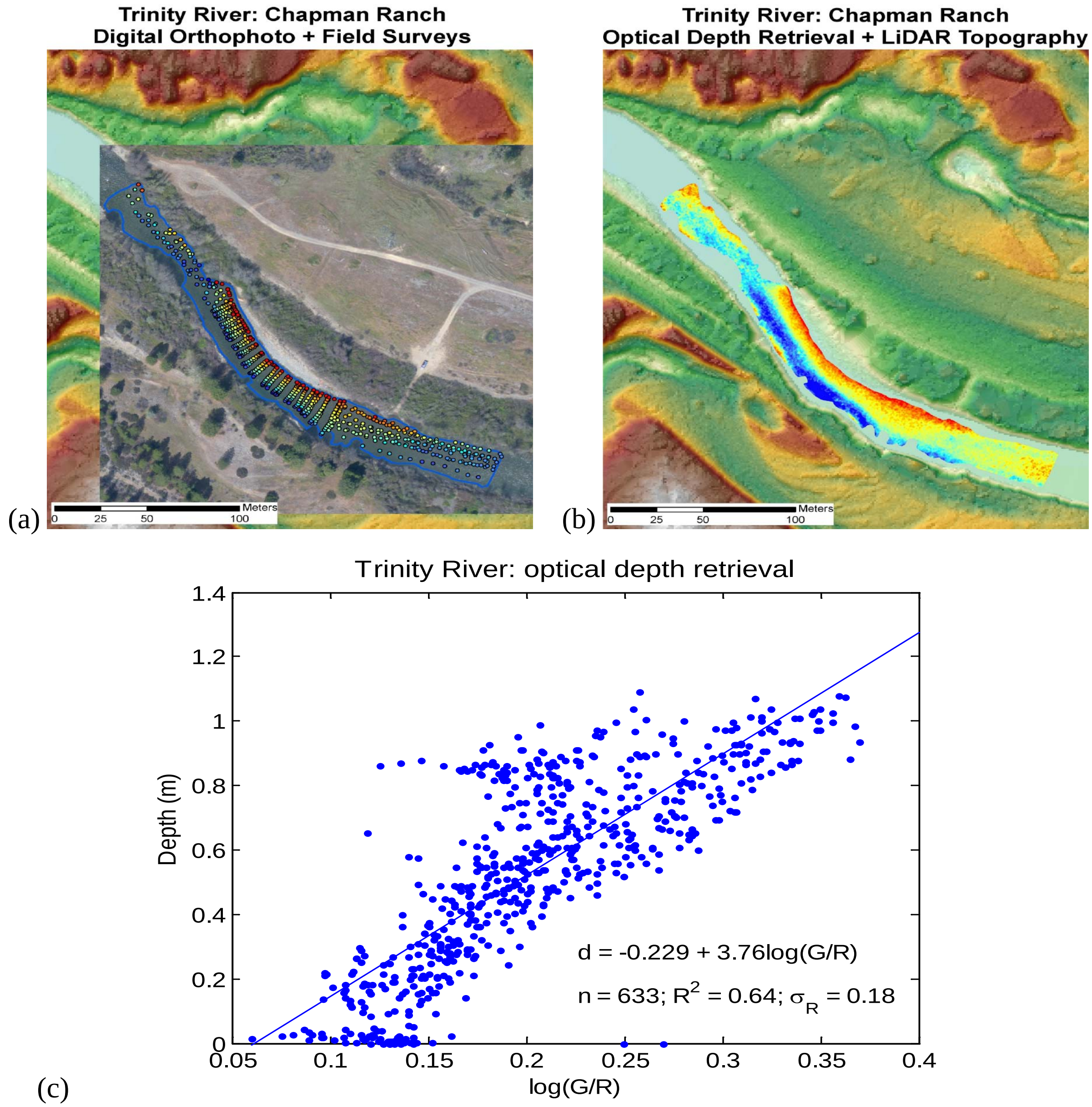


Figure 2. Simple example of correlation between water depth and the logarithm of the ratio of Green to Red spectral bands. (a) Surveyed depths mapped as color-coded points on an orthophoto. (b) Depth using the same color map inferred from the best-fit correlation shown in (c).

data. Constructing computational models of the surveyed reaches using the two different kinds of bathymetric data will then provide a method for assessing to what degree and in what manner computational predictions are affected by errors in remotely sensed data. It is important to note that this assessment of error is distinct from assessing the differences between the bathymetric data sets; this involves understanding how the models respond to differences or errors in the bathymetric measurements. Nelson is a USGS expert in computational modeling of river flow, sediment transport, and bed evolution, and the model assessments will be done with existing USGS public-domain models (e.g., Nelson et al, 2003). Post-doctoral fellow Carl Legleiter (now a faculty member at the University of Wyoming) is experienced at extracting bathymetric information from various kinds of remotely sensed data and at developing equally probably bathymetric surfaces from sparse data sets (Legleiter et al, 2004; Legleiter and Roberts, 2005). Together with Kinzel, they are working on modeling the surveyed sites and comparing model predictions for a suite of bathymetry including the actual conventionally surveyed data and equally probably surfaces developed from the remotely sensed data.

WORK COMPLETED

Based on field efforts over the first 21 months of this ONR grant, the following field data collections and analyses are complete:

(1) Trinity River, California. In 2009, detailed bathymetric surveys using acoustic, RTK GPS, and robotic total station surveys were collected at Sheridan Bar and Chapman Ranch. Bathymetric LiDAR was collected over a 40-mile reach from Lewiston Lake to the North Fork of the Trinity, which includes the sites above. As of this writing, all data has been analyzed and comparisons of the conventional and LiDAR bed surveys have been compared. FaSTMECH computational flow solutions have been completed for both surveys at the Sheridan Bar site (presented at 2009 AGU).

(2) Klamath River, California. In 2009, a detailed bathymetric survey using the techniques listed above was collected at the Indian Creek confluence. Bathymetric LiDAR was collected over most of a 70-mile reach from Iron Gate Dam to Indian Creek. Initial inspection showed that some of the LiDAR data had bad navigation inputs, so that the bathymetry is locally inaccurate. Unfortunately, this included the Indian Creek site. This year (2010), conventional surveys were collected at another site (Tree of Heaven) where the LiDAR is good in order to rectify this issue. Data was analyzed and comparisons were completed.

(3) Colorado River, Colorado. A detailed bathymetric survey using the techniques listed above was collected near the confluence with the Blue River (Kremmling, Colorado). Bathymetric LiDAR was also collected at the same location at the same time. Results are shown in Figure 3. During late 2009 and 2010, data was analyzed and comparisons completed. FaSTMECH model runs were completed for both LiDAR and conventional surveys. Currently, computational model results are being developed for this reach using the SToRM model.

(4) Laramie River, Wyoming. During 2010, a detailed bathymetric survey using the techniques listed above was collected near Laramie, Wyoming. Multispectral data was collected from an airborne platform. Data has been analyzed.

(5) Shenandoah River, Virginia. During 2010, a bathymetric LiDAR survey and a conventional survey were completed at the Island Ford reach of the Shenandoah. This data has been analyzed and the

results of the two surveys have been compared. FaSTMECH model runs have been completed for both data sets.

(6) Platte River, Nebraska. During 2010 contemporaneous ground surveys and hyperspectral scanning from an aerial platform were carried out. Preliminary data analysis of the hyperspectral data is complete.

(7) We worked on developing and testing methods for assessing modeling uncertainties associated with the propagation of bathymetric measurement errors through computational models.

(8) We worked on using morphologic evolution models in combination with roughness estimation techniques to detect and repair errors in remotely sensed bathymetric data sets. The results are very encouraging.

(9) We worked on coupling bedform evolution models to larger scale river models in order to predict the evolution of channel roughness, as is necessary in order to use computational models with remotely sensed data.

In addition to the above completed field data collection efforts (1-6), we hope to complete one additional field data collection effort, probably a bathymetric LiDAR effort on the Kootenai River near Bonner's Ferry, Idaho. Detailed multibeam acoustic surveys already exist for the Kootenai, and this existing data should be appropriate for comparison.

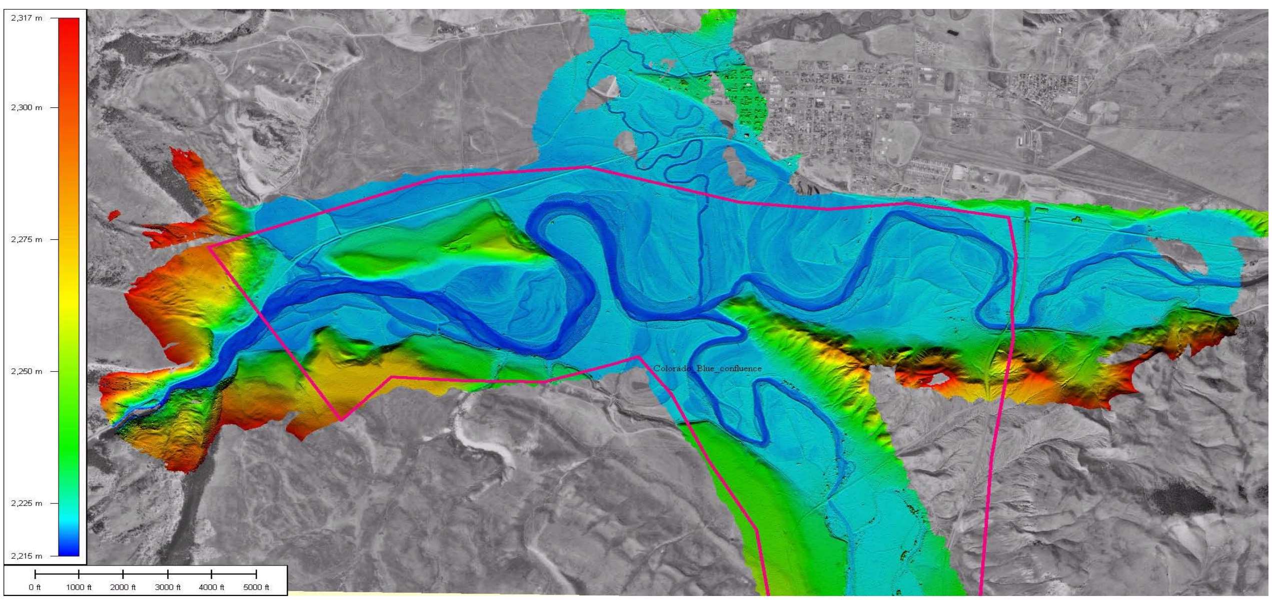
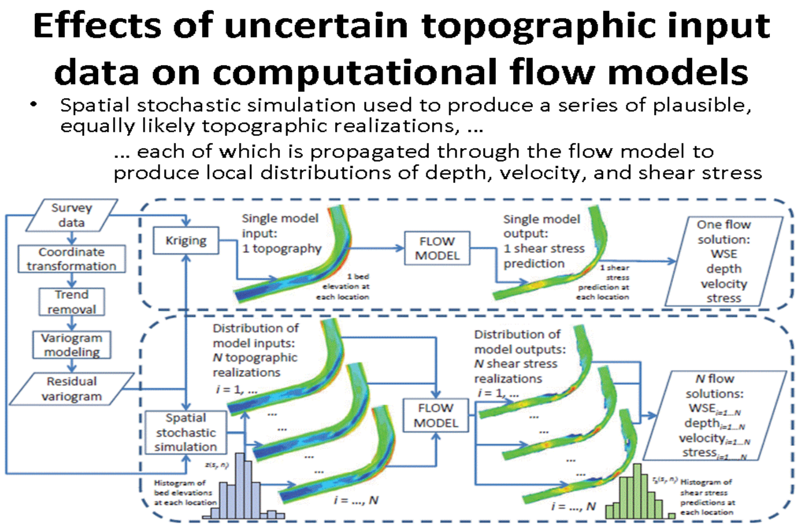


Figure 3. Bathymetric LiDAR results for the Colorado/Blue River confluence.

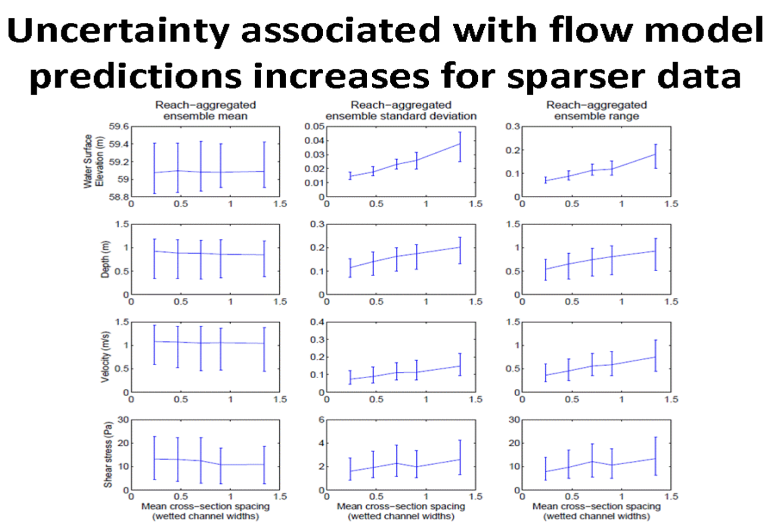
RESULTS

The data set we have collected over the last 18 months forms the basis for a quantitative assessment of the accuracy of bathymetric LiDAR and also is the fundamental part of assessing model errors associated with the use of remotely sensed bathymetry. For the bathymetric LiDAR, our measurements and comparison with RTK GPS survey data (generally accurate to about 2 cm in the vertical), suggest that the LiDAR bathymetry typically has a simple bias of up to 1m, a random error of about +/- 15-25cm, and systematic errors associated with physical issues, including convolved returns in shallow water and missing or weak returns in deep water. For the multi- or hyperspectral data, only depth estimates are provided, so mean bias (relative to true elevation) is not an issue. The spectrally-derived depth estimates generally require in situ calibration and show random errors on the order of +/- 15-35cm even with that calibration. Furthermore, the error range tends to be somewhat correlated with depth itself, with large errors (lower resolution) found at deeper depths. Shadows and other spatial varying optical effects can significantly degrade these results. Unsurprisingly, neither of the two techniques works well when the bed is not resolved due to large depth, low transmissivity or a combination of both.

We are developing error estimates for multidimensional modeling results using the technique described by Legleiter et al. (WRR, submitted). Using this method, measured bathymetry is used to create a suite (typically at least 100 realizations) of equally probably bathymetric estimates. These are generated using the spatial variogram of the measured data and sampling onto a grid. Running any of a variety of models on this suite of bathymetric realizations yields statistics concerning the model predictions. Figure 4 shows a simple example of this technique in which the model errors are estimated as a function of data density. This technique is being used to assess the errors in model predictions associated with random errors in bathymetric estimates, but this is not sufficient to treat systematic errors. To treat systematic errors, we are working on three different methods. First, we are working with the LiDAR data processing tools to minimize this kind of error and to detect these errors when they occur. Second, for errors that we cannot detect or fix as part of the processing, we are using morphologic evolution models to detect areas of apparent inconsistency in the bathymetric estimates and to “repair” those errors using time stepping of the flow and sediment transport conservation equations. An example for the case where LiDAR cannot penetrate to the bed in deep areas is shown in Figure 5. For this case, comparison of the conventionally surveyed data to the remotely sensed data shows obvious missing areas of deeper flow (pools). The bathymetric LiDAR data for this site does not penetrate to the bed in the deepest areas as seen by comparison of Figure 5(b) and (c), hence the pool is missing in the remotely sensed data. However, if we use a simple quasi-three-dimensional flow model along with bedload equations to evolve the topography in time, the missing pool is reestablished in the topography. The interaction between the flow field, the sediment transport, and the bed morphology correctly “finds” and corrects the error in the remotely sensed data. For this case, we started with the remotely sensed bathymetry and computed the predicted bathymetric evolution over three weeks using an estimated bankfull flow of 88 cms and an estimated (single) grain size of 0.25mm.

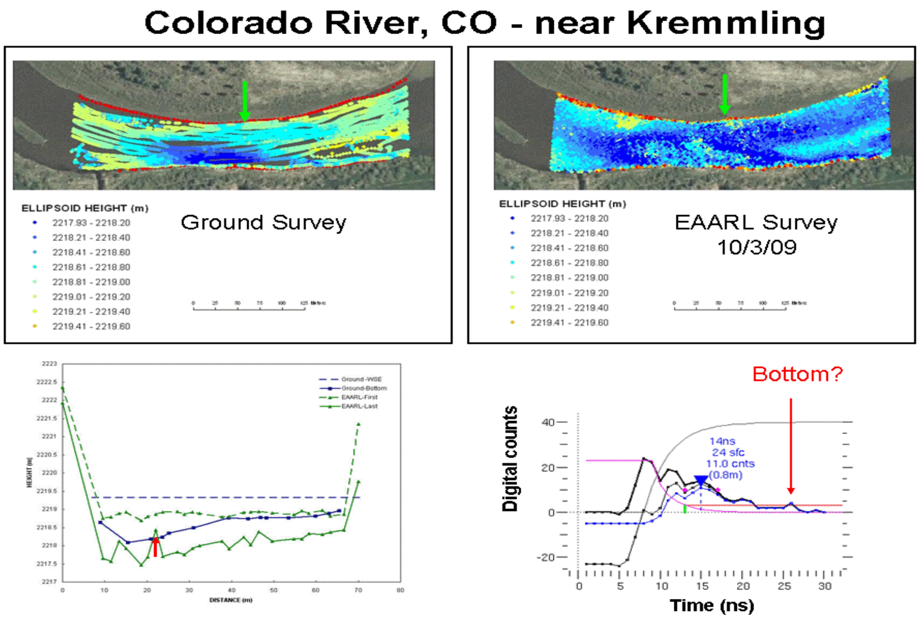


(a)



(b)

Figure 4. Schematic of the methodology for assessing model uncertainty: (a) shows the method of generating equally probably bathymetric realizations, (b) shows the results for common model predictions as a function of decreasing data density.



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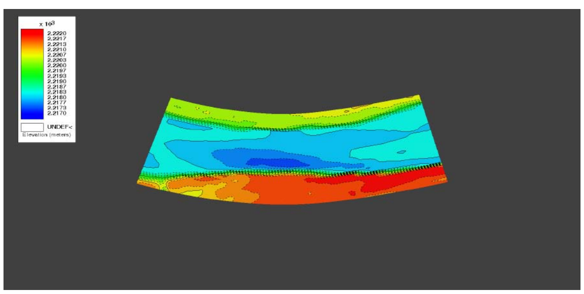

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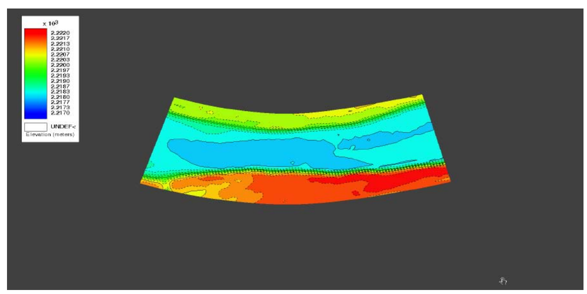

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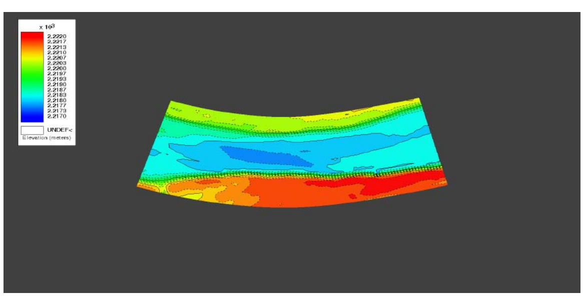

(d)

Figure 5. (a) The conventional and remotely sensed bathymetric surveys along with a cross-section near the mid point of the reach and the LiDAR photomultiplier output, (b) the conventional survey in the model, (c) the LiDAR survey in the model (note errors between (b) and (c)), and (d) the final topography predicted after three weeks of evolution using the bathymetric survey as the initial topography along with an estimated bankfull discharge of 88 cms and a single grain size of 0.25mm.

The model correctly predicts the formation of a pool, and even though the location is not perfect relative to the conventional survey, the result is clearly improved relative to the original remotely sensed bathymetry. In this case, the differences between the "evolved" bathymetry and the observed bathymetry is almost certainly due to the unknown upstream flow condition; for longer reaches, the flow field becomes essentially independent of the upstream condition and we expect even better results. The final method we are using to address systematic errors is through direct computation of the depth using the conservation laws for the flow field but adding information about known water-surface elevation, water velocity, etc. Although a more complete discussion of this method is outside the scope of this report, we believe it is the most promising of all.

IMPACT/APPLICATIONS

Since members of this project first tried bathymetric LiDAR in rivers several years ago and used the resulting data for modeling, the requirement of better characterization of errors and of assessment of impacts of those errors on modeling has not been met, despite increasing use of bathymetric LiDAR for modeling applications. This project will have broad, immediate impact as we offer public domain tools for such applications to other users.

RELATED PROJECTS

At two of our field sites, we have coordinated with the ONR-funded drifter study headed by Jamie McMahan at the Naval Postgraduate School. In addition, several of our field sites are part of various Department of Interior projects, including the Trinity River Restoration Program and the Kootenai River Recovery Program.

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